Rapid response gravitational wave follow-up with the PIRATE robotic telescope

Conference or Workshop Item

Rapid response gravitational wave follow-up with the PIRATE robotic telescope

Dean Roberts & Ulrich Kolb
School of Physical Sciences,
The Open University, UK

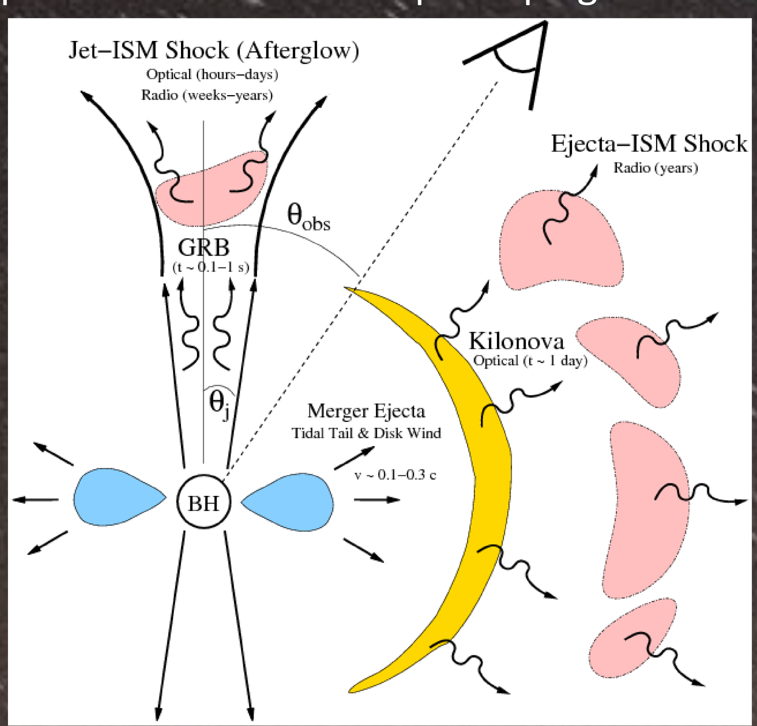
Abstract

This poster briefly outlines the research being undertaken at The Open University in the search for electromagnetic (EM) counterparts to gravitational wave candidates detected by the LIGO/Virgo Collaboration (LVC). This includes the setup of the PIRATE facility, which is a robotic telescope located in Tenerife, Spain, and is used as both a research and teaching telescope. Additionally the poster describes the methods used to perform rapid follow-up to gravitational wave alerts from LIGO/Virgo, and how the images are processed to look for fading transients. Lastly there is a short summary of results from the last observing campaign, corresponding to the second LIGO observing run (O2).

1. Introduction

The existence of gravitational waves (GW) has been theorised for over 100 years, but they were not detected conclusively until 2015 (Abbott et al., 2016), owing to their incredibly weak signal. These signals were detected by the LIGO/Virgo Collaboration (LVC) using incredibly sensitive interferometers, that are up to 4km in length. And since 2015 they have detected gravitational waves emanating from 6 compact binary mergers, and all but one of these were binary black holes. However last August the LVC detected gravitational waves from a binary neutron star merger for the first time (Abbott et al., 2017).

In addition to the GW signal, an electromagnetic counterpart (EM), known as a kilonova (see Figure 1), was also discovered. After a brief gamma-ray flash, the optical signature of this counterpart was dominated by the kilonova process, but this signal rapidly faded by several orders of magnitude in just 10 day (Figure 2). That is why follow-up observations such as these require rapid response times to catch them before they disappear. The observations taken by several observatories of AT 2017gfo showed that with an initial magnitude of ~17 (i-band) (Coulter et al., Soares-Santos et al., 2017), were it visible to the northern hemisphere at this time then it would have also been observable with PIRATE. Nevertheless, PIRATE took part in the EM follow-up campaign for O2 and the results of which are given later.



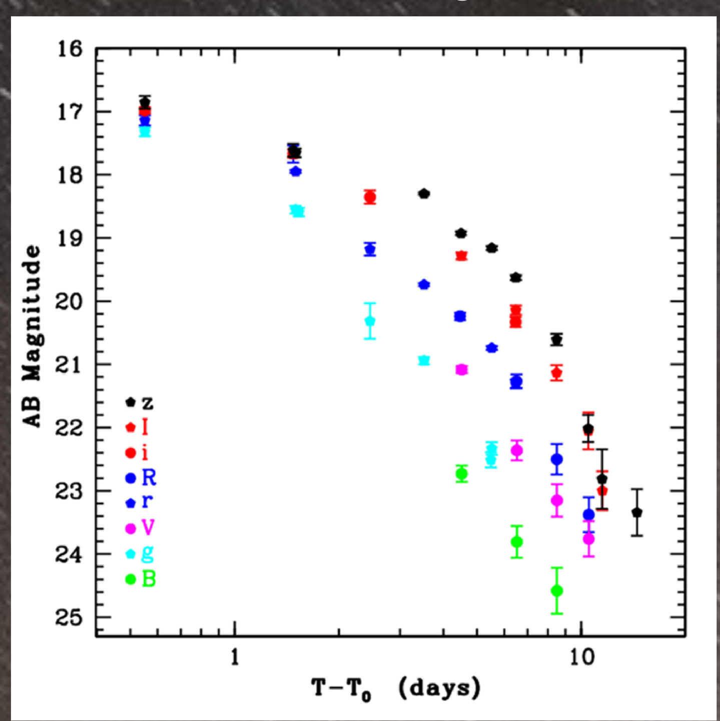


Figure 1 (Left) An illustration of electromagnetic counterparts from binary neutron star mergers. Metzger & Berger (2012).
Figure 2 (Right) Multiband optical light curve of AT 2017gfo using the VLT Survey Telescope (VST) Pian et al. (2017).

2. PIRATE Facility

Previously PIRATE was located at the Observatorio Astronómico de Mallorca where it made important contributions to time-domain astrophysics research projects, such as monitoring exoplanet transits (Gómez Maqueo Chew, et al., 2013) and eclipsing binaries (Lohr, et al., 2015), but it also played a major role in the teaching of undergraduate astronomy courses at The Open University where it was used to teach undergraduate students the basics of telescope operation. However, during 2016 the telescope was relocated to a new site at the Observatorio del Teide in Tenerife where it is now housed in a new 4.5m dome atop the 2400m high mountain, alongside its twin facility COAST (Figure 3).

PIRATE itself consists of a 17-inch (0.43m) optical tube assembly (OTA) mounted on top of a 10Micron GM4000 HPS mount (Figure 4). Attached to the end of the OTA is a an FLI ProLine camera which contains a CCD chip with 16 Mega Pixels, that provide a 43' field of view with a pixel scale of 0.63"/pixel (Kolb, 2014). In addition to this it is equipped with a 7 position filter wheel containing 3 broadband filters (Baader R, G, B), 3 narrowband filters (Hα, OIII, SII) and a clear filter. The telescope is controlled by an automated observatory control software called ABOT that allows students and staff to control the telescope in real time over the internet; as well as schedule observations to be taken during the night. ABOT is also deployed for BlackGEM, Solaris and MeerLICHT (Sybilski, 2015).

Figures 3 & 4. The PIRATE telescope by day in the shadow of Mt Teide and at night under the Milky Way . Image Credits: Johannes Baader

3. Method

One of the key advantages in using a robotic telescope is the rapid response times it can achieve for any astronomical alerts of interest, such as gamma-ray bursts and gravitational waves. However to utilize this it was necessary to create a bespoke pipeline that would process the incoming alerts quickly, but more importantly, without any human intervention. The result was a Python script built on one written by Leo Singer (Singer, 2015) to receive and process gravitational-wave candidate alerts from Advanced LIGO and Virgo via GCN alerts (see Figures 5 & 6).

The alerts contain a sky localization probability map (known as a skymap) and the key step in this process is deciding which areas of the skymap to observe given their relatively large size. Currently this is done using a simple method of highest to lowest probability and with a maximum number of observations cut-off. However an alternative way would be to target individual galaxies within the search area, such as those in the Gravitational Wave Galaxy Catalogue (White, Daw, & Dhillon, 2011), and even potentially in a 3D search volume using the new 3D skymaps (Singer, et al., 2016).

Once the data is calibrated we use the source extraction software SExtractor (Bertin E., 2010) to perform photometry, which then gets passed on to a variable star detection software VaST (Sokolovsky & Lebedev, 2017). This generates lightcurves for all the stars in a reference image across the dataset; and it then uses multiple variability indices to show which stars have high variability across the time series. The index we rely on is the ratio of the variance over the mean square successive difference, which highlights stars with variability over longer time scales.

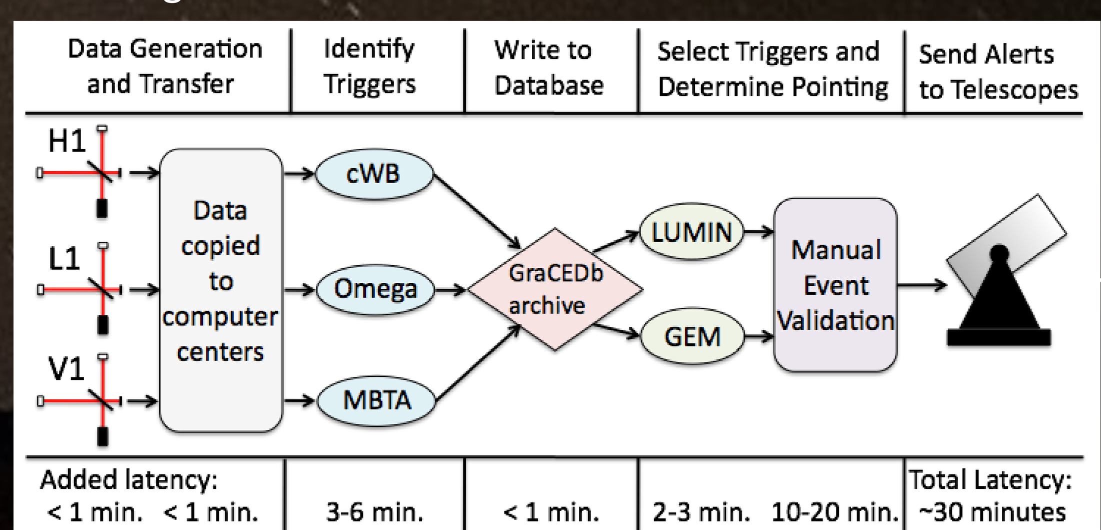


Figure 5. A flowchart showing the different stages of LIGO GW trigger analysis. Image Credit: LIGO/Virgo Collaboration

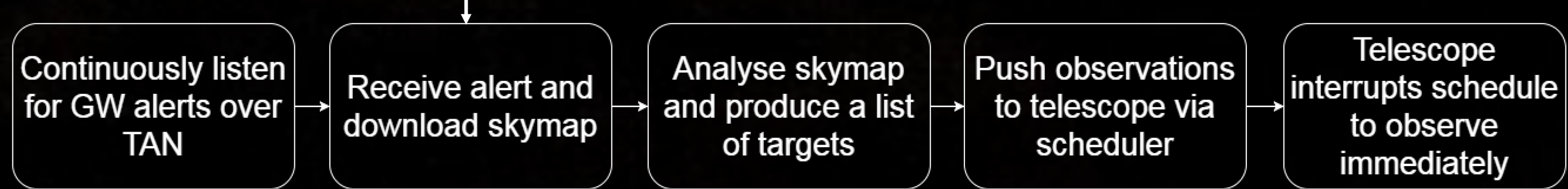


Figure 6. A flowchart highlighting the different stages of the PIRATE alert pipeline.

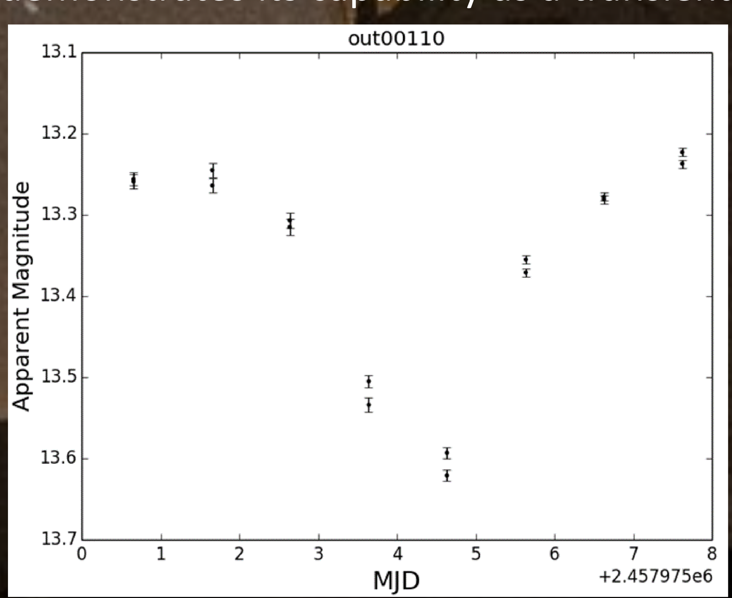
4. Results

The second LIGO observing run (O2) ran from 30th November 2016 to 25th August 2017 and during this period they released 10+ alerts to the observing community, of these PIRATE was able to follow up 70% to some degree. For 4 of these we have 7+ days of observations, which cover around 35 fields of view, in total we obtained 70 nights of observations comprising of over 2,000 images.

Having processed all the data we concluded that no unexpected transients were detected in our data, however all the alerts we followed up originated from binary black hole mergers which aren't expected to produce an electromagnetic counterpart.

The plot in Figure 7 shows the lightcurve of a previously known W Uma class variable star, that was serendipitously detected while performing our follow-up observations, and there are dozens more similar examples to this in our data set.

Lastly, the plot in Figure 8 shows the lightcurve of the MASTER OT J033744.97+723159.0, which was a Type IIb supernova discovered pre-maximum by the MASTER group while performing follow-up observations of another LIGO alert. We were able to observe this target for over 60 days with PIRATE which demonstrates its capability as a transient follow-up telescope.



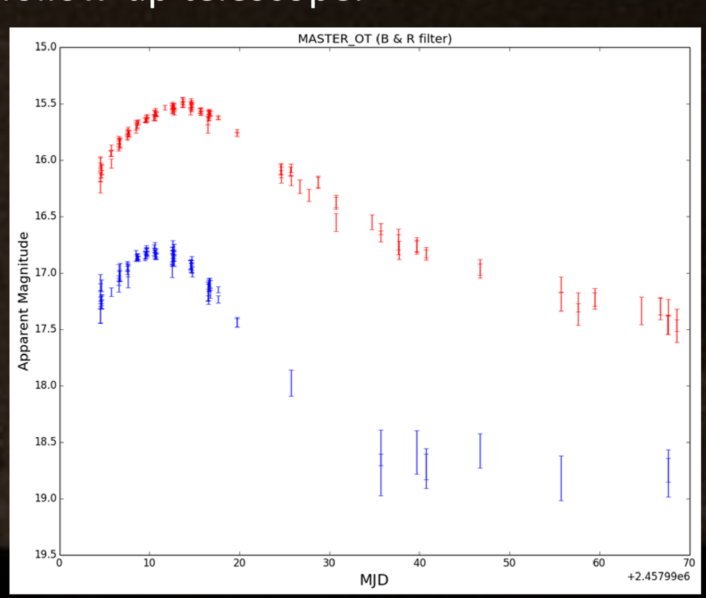


Figure 7. The lightcurve of a W UMa type eclipsing binary, detected while searching for GW counterparts.

Figure 8. Two lightcurves in Red & Blue filters of a Type IIb supernova, first discovered by the MASTER network.

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Background Image: Edward Hand